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DATA ANALYSIS AND COMPRESSION TECHNIQUES FOR MEGABYTE-DATA PDE EXPERIMENTS

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Abstract

Pulsed detonation engines have the potential to provide thrust over a wide operating range for a fraction of the cost of conventional turbine engines. These promised returns have given rise to several vigorous research programs in academia, industry, and government labs. To capture the ultra-fast events comprising a detonation wave, researchers are forced to use megahertz range data acquisition systems for relatively long testing intervals, producing gigabytes of purely numeric test data. Since human inspection of such enormous data sets is virtually impossible, a computational framework of highly automated analysis tools is necessary to facilitate the interpretation and analysis of pulsed detonation engine experiments. A variety of software algorithms can be applied to produce meaningful output for rapid human assimilation. Dynamic pressure transducer data can be filtered to remove non-linear drifting of the baseline, scanned to locate each captured detonation, and condensed to produce small, highly representative point sets for subsequent analysis. Wave speeds, firing frequencies, thrust estimates, and output shaft work can all be automatically calculated through the use of intelligent, adaptive analysis routines. Data from different sensors, including high speed imaging systems, can also be combined into visual, animated interpretations to facilitate rapid qualitative understanding of experimental results. Finally, digital finite impulse response filters, cycle time reference signals, and floating average reference lines can all be utilized to eliminate noise and extract equivalence ratio data from passive OH emission and active hydrocarbon absorption sensors. By preprocessing these complex signal files with automated routines, the cost-effectiveness of data intensive research programs can be maintained and key results can be successfully extracted from a myriad of noisy, machine-readable raw data.

Introduction

Over the last several years, Air Force Research Lab's PRTS (Combustion Sciences) division has been conducting in-house research on an air breathing pulsed detonation engine.[1] This effort reflects a general trend toward renewed interest in the potential of PDE technology. Since such engines produce phenomena traveling on the order of 10^3 m/s, megahertz range data acquisition is required to gather meaningful experimental data sets. Frequently, the sheer quantity of collected information prevents its efficient examination and evaluation by researchers. This paper will discuss several software techniques and computational algorithms used to automatically analyze, interpret, and reduce the enormous data files produced from these high speed sensing systems. Such automation provides investigators with near real-time feedback on testing results.

A variety of sensor systems are employed during PDE testing. First, dynamic pressure transducers are utilized to study detonation structure, measure wave speeds, and estimate output thrust. These transducers can also be used to estimate the work output from variable frequency PDE engines. Recent work involving passive OH emission and hydrocarbon absorption diagnostics will also be addressed.

The test facility used to acquire the sample data sets features a typical high-speed data acquisition system. Two National Instruments data cards are controlled by a custom LabVIEW virtual instrument and can each acquire four voltage signals simultaneously at five megahertz, producing up to forty million data points for each second of run time. Typically, the cards are used at one or two megahertz for 500 to 1000 millisecond sample intervals. As a result, gigabytes of data are produced during weeks of

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heavy testing. The following sections describe the various tools and algorithms that have been developed to process data files of this size from a variety of sensor types.

Dynamic Pressure Transducers

Pressure transducers offer numerous exciting insights into detonation studies. These transducers can yield pressures, detonation velocities, thrust and work output measurements, and valuable information about the structure of dynamic detonation and blow down events. These benefits are greatly amplified by using a linear arrangement of several accurately spaced transducers along the detonation cavity. The dynamic pressure transducers were used on engines with both constant and variable firing frequencies.

Constant Detonation Frequency

Frequently, research PDE's are mechanized by an external motor, producing a nearly constant firing frequency.[1] The following section describes several analysis procedures for data files collected under these conditions.

Cycle Isolation

Before any calculations can be performed, it is necessary to locate the Von Neumann spike, or peak pressure on deflagrating channels, associated with each detonation on each channel of the data file. These spikes are relatively easy to identify and have a virtually constant temporal position within the engine cycle, thus providing a reference for further processing.

Unfortunately, the pressure transducers, like many sensors, frequently have a DC bias, and this baseline can change levels throughout the run. When data is collected for longer intervals, this floating baseline can vary non-linearly over a range greater than the signal amplitude. To compensate for this thermal drift, two options are provided to the user. For short data runs, the software calculates the average DC bias

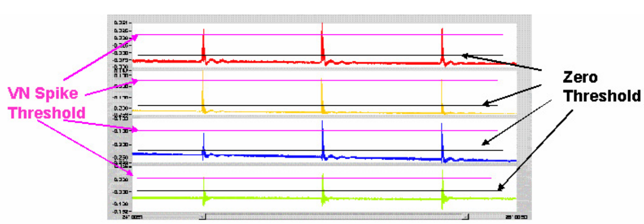

Figure 2. Threshold Illustrations.

of the flat portions of the signal and subtracts out this constant offset. For longer runs, the algorithm segments the data into small pieces that are approximately equal to the firing interval and performs a linear regression on

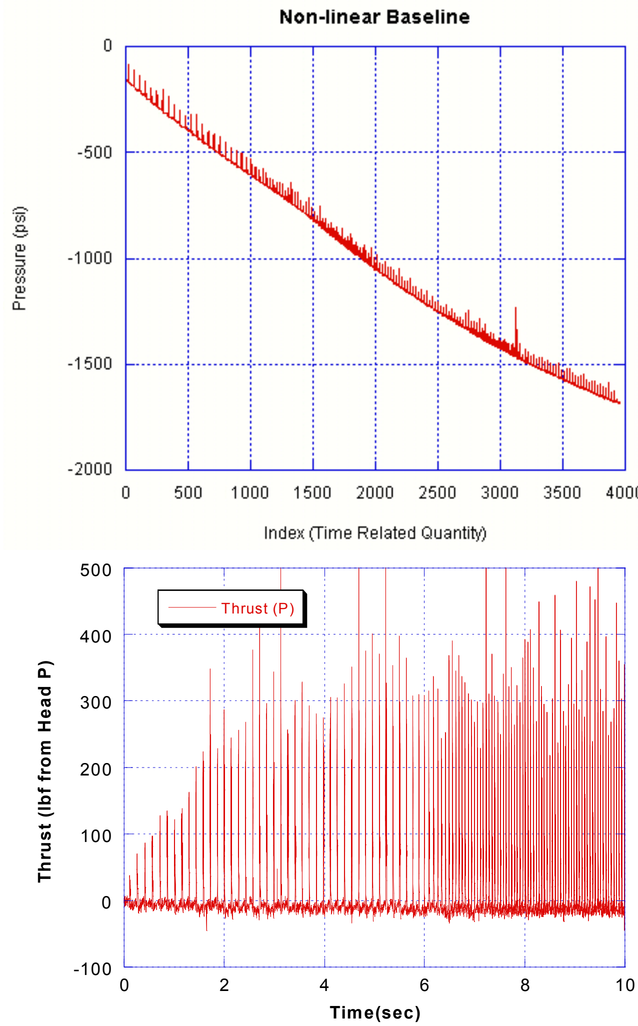

Figure 1. Non-linear baseline sample (top) and a corrected output file.

the flat portions of each segment. This piecewise linear baseline is then subtracted out to flatten the signal. Figure 1 shows a highly contaminated data trace before this procedure was applied and a sample output from the algorithm.

After removing noise contamination from the data's baseline, a threshold is selected based on the anticipated Von Neumann spike amplitude. This threshold is then scaled by one fourth to produce the zero threshold, as shown in Figure 2. Groups of points above the Von Neumann threshold are marked as possible detonations. If two groups of points are not separated by at least a few points below the zero threshold, then those groups are considered to be a single detonation. This process prevents a single detonation from being counted several times. Next, the highest point in each group is marked as a Von Neumann spike. In most cases, this algorithm locates

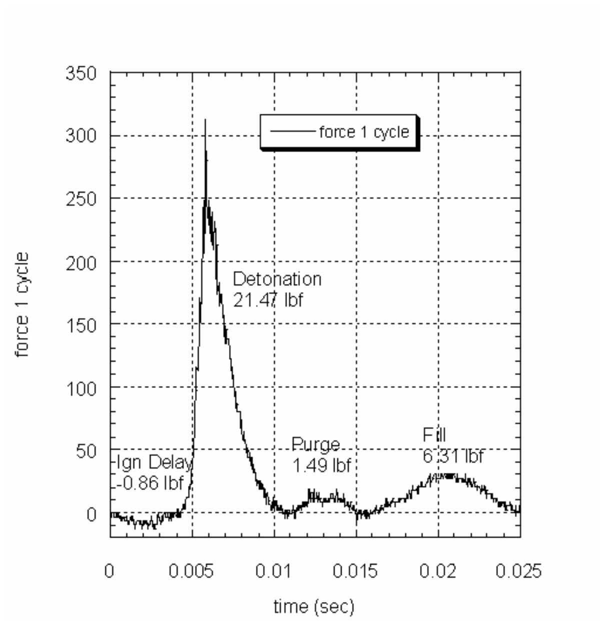

Figure 3. Sample thrust calculation.

extra spikes and misses some low-amplitude peaks. To compensate, a second search pass is completed. The trace with the most consistent spike spacing (i.e. the standard deviation of the spacing interval is the lowest) is assumed to be correctly marked. The other channels are then checked to verify that they contain a Von Neumann spike in each region where the baseline channel has one. Extra spikes are discarded, and missing spikes are filled in with the highest point in the corresponding cycle's time interval. This two pass technique was able to locate all Von Neumann spikes in the vast majority of test files.

Direct Calculations

Once the Von Neumann spikes are located, the algorithm searches backward from each spike until it sees the beginning of the pressure rise. These points are saved and used to separate the data file into pieces, each of which contains a single firing cycle. With the detonations separated, several calculations can be completed. First, wave speeds can be calculated directly from the Von Neumann spike time indices combined with the physical spacing of the transducers. Wave speeds are calculated using the Von Neumann spike time, the time associated with the beginning of the pressure rise, and the time at which the wave reached half its full height. In general, the middle or half-height wave speeds were the most consistent.

In addition, numerical integration of the pressure traces was used to verify static thrust stand measurements. However, once the thrust stand accuracy was verified using pressure transducers, this technique was not frequently employed. Transducer noise, coupled with the sheer number of data points, make static thrust measurements much more robust and efficient when a thrust stand is available. Figure 3 shows a sample thrust calculation using dynamic pressure transducer data.

Data Compression

High speed data acquisition is necessary to capture the detonation wave peak passing the transducers at 2000 m/s. However, the vast majority of the data file is redundant, recording atmospheric pressure or drastically over-sampling the steady P_3

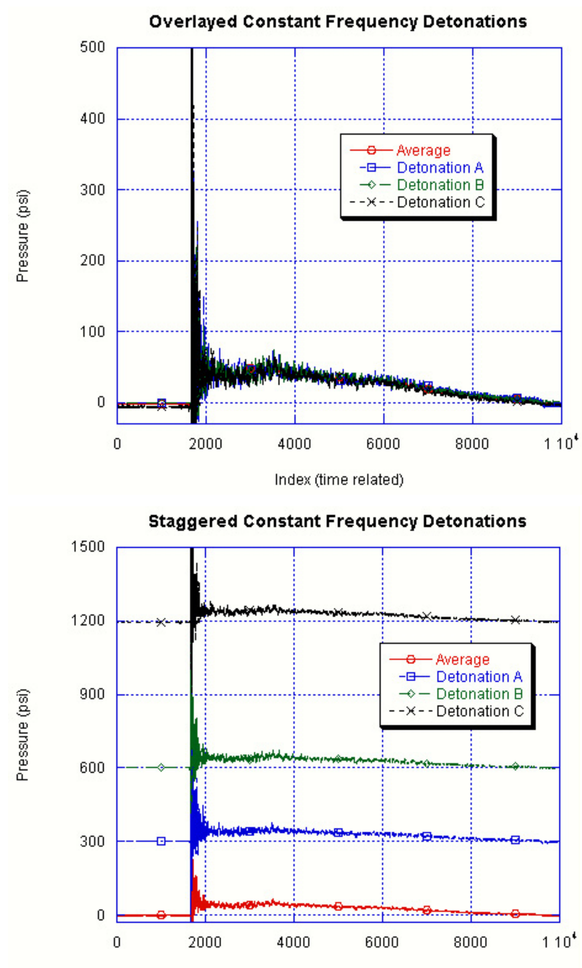

Figure 4. Constant frequency detonations.

thrust and blow down portions of the combustion event. One major goal of the analysis software is to condense these binary fifteen megabyte files to a more manageable format. Trace averaging and compression are both employed to reduce the file size while preserving the useful original information.

After the detonations have been separated into individual files, they are correlated so that their Von

Neumann spikes overlap. Often, individual cycles on a given channel have slightly different lengths. Zeroes are added to the ends of each detonation to make the total number of points in each cycle the same. Next, each trace is replaced with the numerical average of all the cycles on that channel. Zeroes are then added again to make the relative lengths of the data channels correct (i.e. so that the apparent wave speeds of the average detonation would be equal to the average calculated wave speeds) and combined to form an average cycle for output. This process reduces the file size dramatically and helps to eliminate Gaussian noise introduced by the pressure transducers. Figure 4 illustrates that the constant frequency conditions yielded highly self-similar detonations. As a result, the structure of the detonation was preserved during the averaging process.

To further compress the file, redundant points are then removed from the average pressure traces. The filter scans through the file and keeps the first, middle, and last point in each segment of the file that varies by three psi or less. This filtering removes high frequency, low-amplitude noise and drastically reduced the file size. Figure 5 shows a filtered file whose size was reduced by a factor of six without any perceptible loss of information content.

Variable Detonation Frequency

Some PDE data sets, such as those conducted with a self-actuating PDE[2], have a variable firing frequency. Since the spacing of detonations is no longer constant, a unique set of analysis tools must be developed to handle such input files.

Calculating the Firing Frequency

Since the firing frequency is not constant within each data set, the cycles are not highly self-similar and the two pass algorithm for locating Von Neumann spikes becomes useless with variable frequency data files. Fortunately, several techniques can be applied to correct this problem. First, a more complex single pass algorithm can be used to locate each detonation event without making the assumption of constant spacing. Unfortunately, such algorithms are difficult to adapt to a wide range of input data types and frequently produce unreliable output when confronted with special cases.

A more effective technique involves using a separate data channel to provide information on the engine's physical position. Optical encoders, rotary position encoders, or a signal from the ignition system could all be used to provide periodic position fixes. The test data was acquired from a Hall Effect sensor mounted on the engine valves that provided four pulses during each firing cycle. By locating these pulses, the

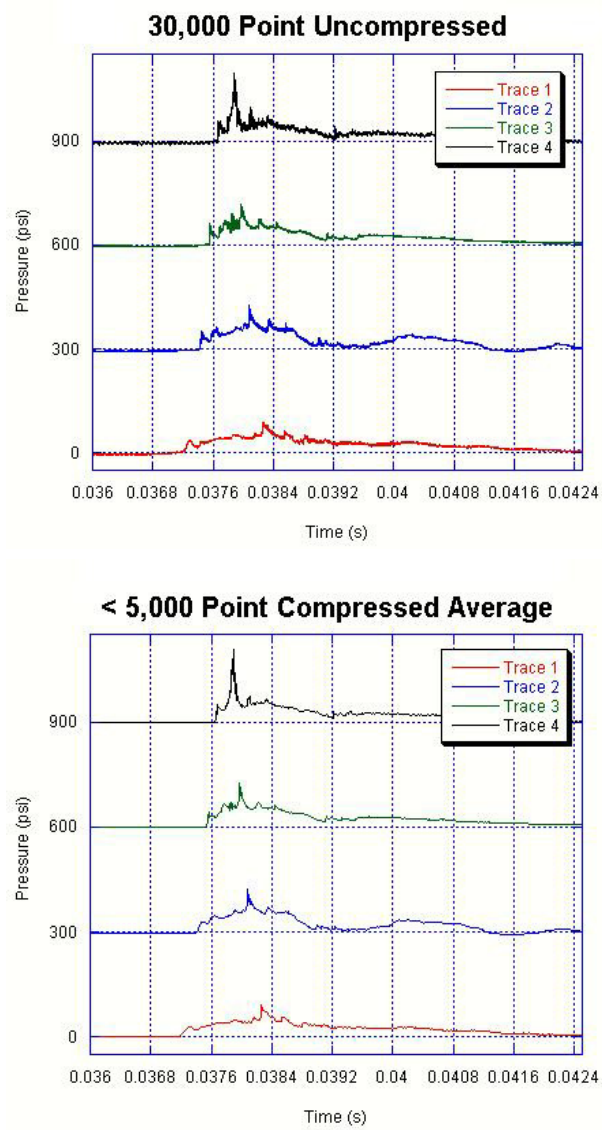

Figure 5. Uncompressed transducer data (top) and compressed output.

instantaneous firing frequency could be calculated four times during each detonation event. Figure 7 shows a typical output from this algorithm. This position data can also be used to isolate individual cycles and calculate the shaft work output from the engine.

Calculating Work Output

The primary purpose of the self-actuating engine was to demonstrate that shaft work could be extracted from the PDE.[2] Thus, the shaft power output from the engine needed to be calculated. Combined with the piston position, the firing frequency could be used to calculate the piston velocity at any time. It was assumed that the engine's angular velocity was constant in between readings from the Hall Effect sensor, and the velocity of the piston was computed as a function of

time. The velocity, when combined with the piston geometry, yielded the differential of the cavity volume. The shaft work output could then be calculated as:

Work = ∫ Pressure d(Volume).

Figure 7 shows a typical output power plot.

Visualization

A linear arrangement of pressure transducers produces an inherently three dimensional data set whose pressure readings are located temporally and along a single spatial dimension. While two-dimensional representations of this data can be interpreted (Figures 2-5), it was decided that an animated, three-dimensional representation of the pressure data would provide qualitative insights into the detonation wave propagation. Detonations were also filmed at high speed to provide insights into the flame behavior.

Animating Pressure Data: Video Trace 1.1

A general animator applet was written in the Java programming language, and a dynamic-link-library (DLL) was constructed in the C programming language to preprocess the data. Before animation, the data is decoded into an ASCII format, arranged in time-stamped columns, and scanned to locate the beginning of the first detonation event. The applet then evaluates the file, selecting an appropriate scale, creating icons to represent each transducer, and selecting a suitable frame rate for the animation output. Finally, each data point, consisting of a time index and pressure readings at several locations, is converted into a JPEG frame and rendered to the screen. Figure 8 shows a single frame of the resulting animation. The grey icons represent the actual data values. Since the pressure transducers often ring, oscillating rapidly after the pressure rises, the green level-bars were added. These slow-changing visual references allow the eye to follow the overall trend in the pressure reading without becoming confused by the oscillatory behavior of the transducers.

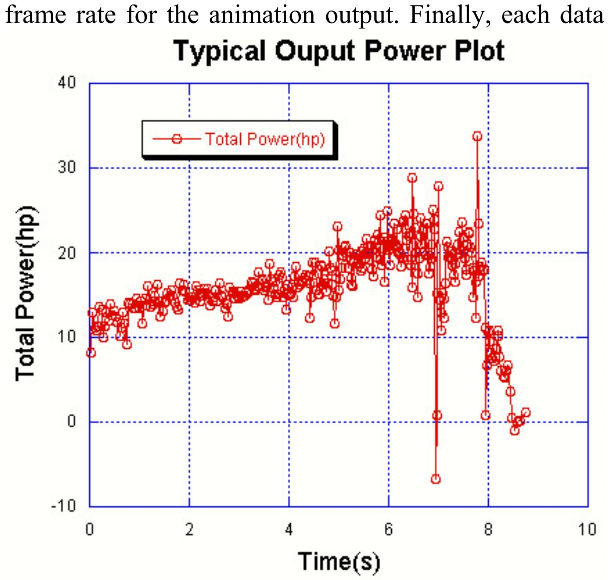

Figure 7. Output shaft power plot.

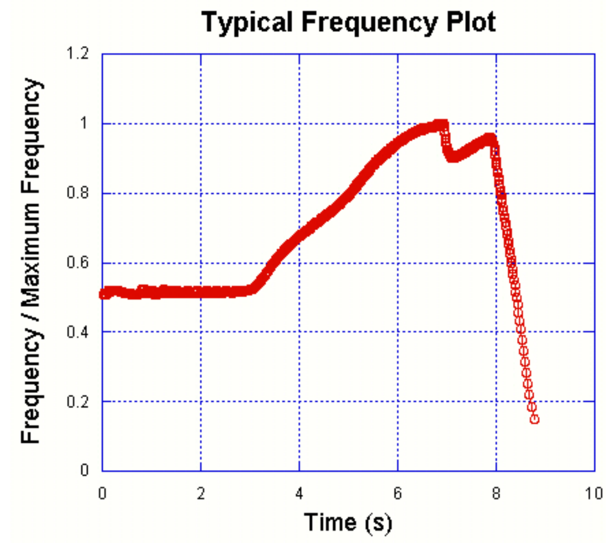

Figure 6. Frequency plot.

The animator can accept from 1 to 100 separate data channels, allowing the applet to be used for large data acquisition files. Also, since both the frame rate and axis limits are auto calculated, a wide range of sensor inputs can be animated without source code modification. Finally, writing the code to directly accept ASCII input files or to preprocess binary files with C language DLL's allows high flexibility in the selection of acquisition software.

High speed Imaging

Detonation waves propagate at approximately 2,000 m/s. In order to evaluate the effects of various tube geometries and detonation ignition schemes on these fast detonation and propagation events, high speed image data were acquired. The imagery was collected using a Phantom v5.0 high speed camera from Vision Research capable of 60,000 frames per second at 32x256 pixels with a maximum resolution of 1024x1024 pixels at low speeds. Visually accessible polycarbonate tubes and steel tubes with polycarbonate windows were used to capture the waves traveling perpendicular to the lens. Through the use of mirrors, the camera was also used to film detonations approaching the lens down the length of the tube. The video provided crucial insights into the mechanisms of DDT (detonation deflagration transition) and the effectiveness of various detonation enhancers.[3]

Synchronization: Video Trace 2.0

Pressure data was recorded along with the high speed video. There was no certainty that the visual manifestations of the traveling wave corresponded spatially with the pressure pulse. In addition, interpreting the pressure and video data separately proved to be arduous and relatively futile. Ergo, a second animation applet was developed to combine the data from these two drastically different sensing systems. The voltage spike from the first pressure transducer was used as a trigger for the camera acquisition. In this way, correlating the data would be possible during post-processing.

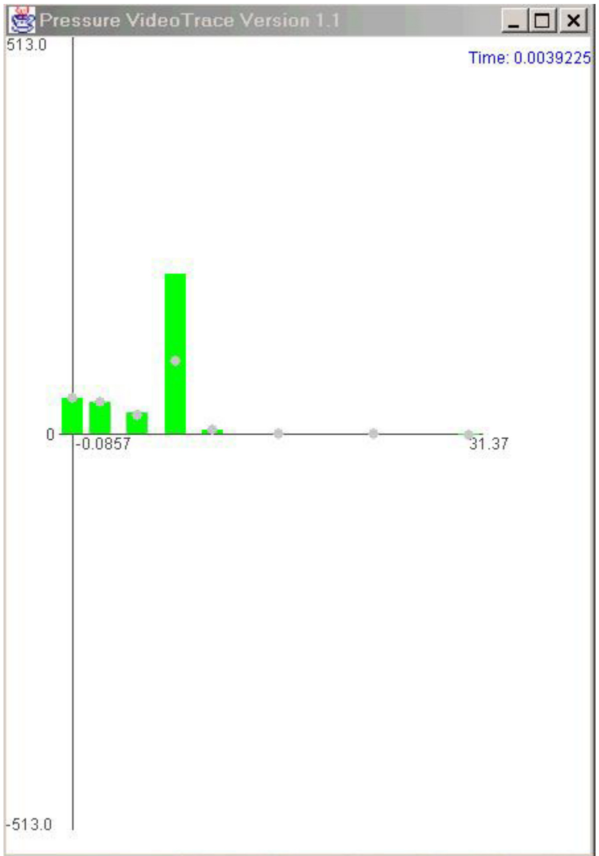

Figure 8. Video Trace 1.1 sample frame.

Once the video was collected, each frame was converted into a JPEG file. A new DLL scanned through the binary data from the pressure transducers and located the voltage spike that triggered the camera. Next, a data point was extracted from the pressure data for each frame of the acquired video. These points were then passed to the second generation animation applet.

The new applet had a considerably more complex rendering task to perform. First, the pressure data was evaluated and the ordinate scaling was determined. In order to compute the screen abscissa values for the pressure data, it was necessary to create a linear mapping from the physical measurements of the tube to the pixel mapping of the image. The mapping was done in software, and the user only needed to provide the physical locations that corresponded to each of the image edges. Once the mapping was complete, each transducer icon was placed at the correct abscissa position to align the pressure data with the physical location of the transducer in the image. Finally, each frame was rendered with the high speed image and the corresponding pressure data point.

Figure 9 shows a sample frame from the output. Several test runs illustrated that the pressure pulse and the visible flame were traveling together with minimal differences in their positions and velocities. The use of high speed imagery in conjunction with

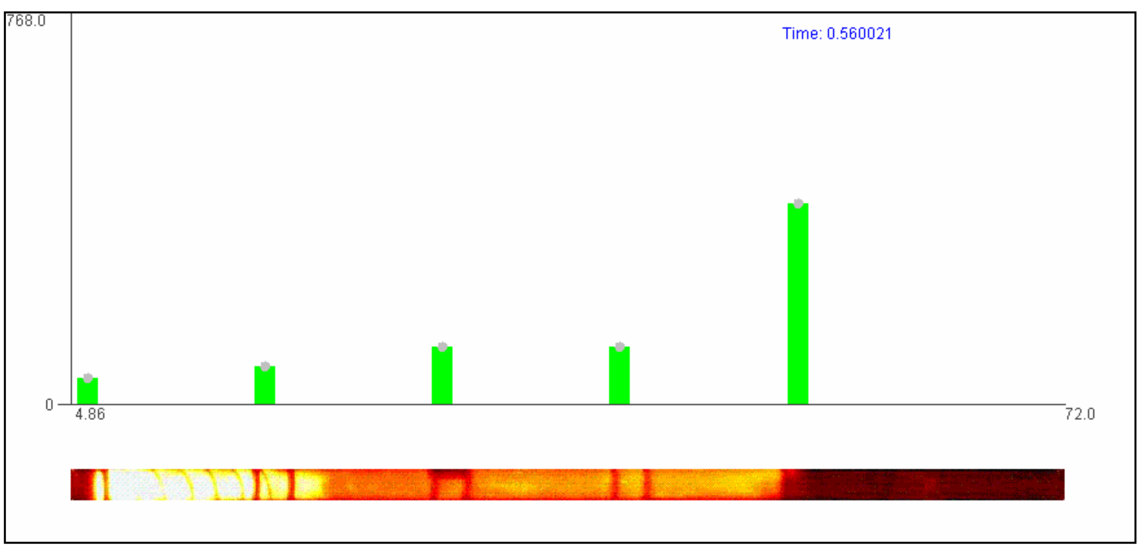

Figure 9. Video Trace 2.0 sample frame.

dynamic pressure transducers to qualitatively evaluate the phenomena occurring in a pulsed detonation engine was found to be highly insightful.

Equivalence Ratio Determination

Pulsed detonation engine performance depends largely on the fuel/air equivalence ratio (Φ) in the detonation cavity. In most situations, stoichiometric ($\Phi = 1$) conditions are ideal, although lean ($\Phi < 1$) and rich ($\Phi > 1$) conditions are often evaluated. Two goals were pursued with equivalence ratio measurement. First, a small, cost-effective, passive sensor was developed for use in a closed loop fuel controller. Secondly, a more complex active technique was developed for studying the fill history of the detonation tube and calculating the equivalence ratio more precisely.

OH Emission

A passive emission sensor is utilized to detect the OH produced by the combustion event. Light from the detonation is passed through a 310 ± 5 nm interference filter and onto a photo cathode. Energy at these frequencies is emitted by the A-X (0,0) electron transition of the OH species. The resultant current is then amplified and converted to voltage for sampling. A substantial test matrix demonstrated that the integrated area of the signal pulse is highly correlated to the equivalence ratio of the detonation for both hydrogen and aviation gasoline fuels.[4,5,6] Figure 10 depicts a typical OH signal for a single detonation.

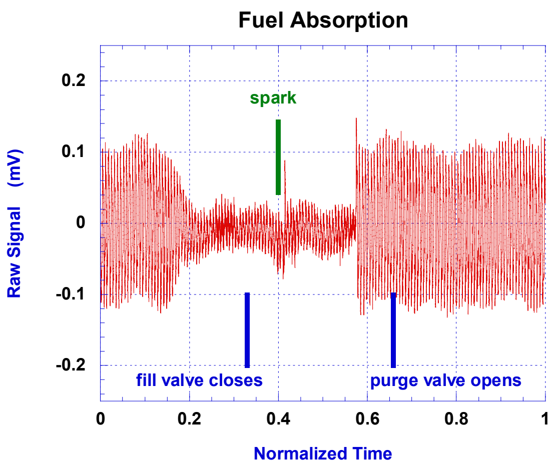

Figure 11. Typical hydrocarbon absorption signal.

Since the emission data would eventually be processed in real time by a microcontroller, extensive software processing was not developed. Instead, an extraction routine was developed to separate the data into under-sampled ASCII files for analysis in commercial signal processing packages. The software also used the techniques previously discussed to calculate wave speeds from simultaneously acquired pressure transducer data.

The significant processing insight with the OH emission data was to use the engine spark signal to segment the data file. In previous constant frequency experiments, the intricate two-pass approach was necessary to scan through the file and separate the individual detonation cycles. For the OH data, a 5 V TTL pulse is generated at the beginning of every firing cycle and recorded along with the other data streams. As a result, the analysis algorithm can make precise cuts between cycles with almost no ambiguity or overlap. The benefits of this precision were more fully realized with the active hydrocarbon absorption sensor data discussed in the next section.

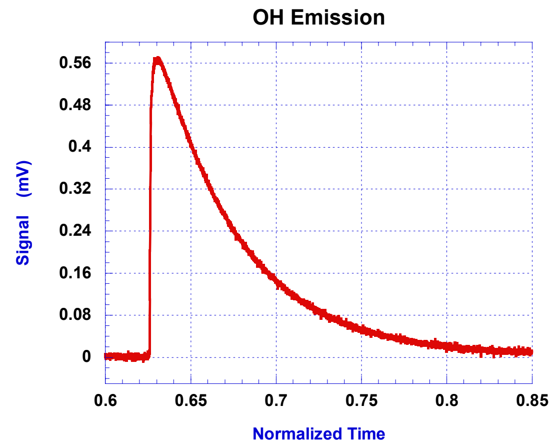

Figure 10. Typical OH sensor data.

Currently, efforts are underway to integrate the OH emission sensor into a small, self-contained package for closed loop fuel control. A microcontroller network will interrogate the sensor and use the calculated Φ values to implement a digital proportional integral derivative controller on the fuel injection systems.

Active Hydrocarbon Absorption Sensor

An active hydrocarbon absorption sensor was developed to characterize the equivalence ratio as a function of time during test runs. A 3.39 µm helium-neon laser was utilized to excite the hydrocarbon fuel reactants. The beam was passed through a mechanical chopper wheel, yielding a signal frequency of 1.5 to 3 kHz, and the uncooled lead selenide detector output was AC coupled to the data acquisition system.[5, 6]

Figure 11 shows a typical raw data signal. The equivalence ratio is related to the negative of the logarithm of the normalized peak-to-peak cycle height

by the Beer-Lambert law. Calculating the indicated equivalence ratio as a function of cycle-normalized time is the primary analysis objective (Figure 13). Since

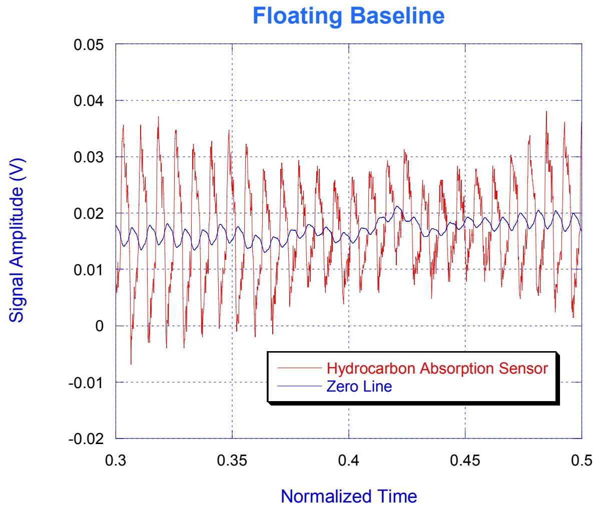

Figure 12. Reference Line to compensate for floating baseline.

each file requires approximately twenty input parameters, the software was written for batch processing. The user enters the geometric parameters for the test run, the constants required for application of the Beer-Lambert law, and several other user processing options for a large group of files into a spreadsheet. The software then processes the entire set of files without additional user interaction. Several data processing challenges were overcome to enable analysis of the multi-gigabyte hydrocarbon absorption data set.

Signal Noise

While the input signal is relatively clean, occasional noise spikes produce absurd equivalence ratio values. While easily corrected by manual inspection, these outliers prevent the use of the full automated potential of the analysis software. To compensate, the software was rewritten to apply a digital finite impulse response filter to the raw data before processing. The coefficients of the filter were read from a user input file. In most cases, a fourth degree, fifty point Savitzky-Golay smoothing filter was utilized. However, by writing the software to generically apply the coefficients of an input file of arbitrary length, any digital finite impulse response filter could be applied without source code modification. This filtering maintained the peak heights correctly and simultaneously eliminated one or two point anomalies.

Floating Zero Line

The peak-to-peak amplitude of each cycle is determined by locating pairs of adjacent extreme points, one below and one above 0 volts. Despite the AC coupling, entire cycles of the signal sometimes remain above 0 volts. This phenomenon is particularly common when the peak-to-peak amplitude was at a minimum value. Unfortunately, these small amplitude oscillations represent the highest equivalence ratio obtained during the run, and their interpretation is absolutely paramount. Since both extreme points are above zero, such cycles are missed entirely by the search algorithm. As a result, the original program often reported an unrealistically low value for the highest equivalence ratios obtained.

To correct this problem, a new line was created to separate the high and low portions of each cycle. Rather than assuming that zero volts was the middle of the cycle, this constructed line was used. The reference line was created by taking a 1,000 point floating average of the raw signal. This average was relatively flat, yet still followed the general contours of the raw signal. The peaks, both positive and negative, always fell on the correct side of this new ‘zero’ line. Figure 12 illustrates a corrupted data file and the zero line that allowed it to be processed correctly.

Background Absorption

The peak-to-peak height before fuel flow begins is used to normalize the heights obtained during the firing cycles. Initially, cold flow data was used to set this reference intensity level. However, heating of the probes, electrical noise, and other factors often caused the base value to drift in between firing cycles. Thus, the algorithm was rewritten to auto-calculate a new base value for each detonation in the file. The largest several heights in each detonation are averaged, and this new value for the zero fuel level was used to calculate the equivalence ratio for that detonation.

Cycle Time Reference

As discussed in the OH emission section, the active hydrocarbon absorption data is collected along with a 5 volt TTL square wave that was synchronized to the engine valves. As a result, the software has a precise reference for the beginning and ending of each cycle. Thus, the code was able to create a normalized time index for each detonation. Beyond making the data easier to interpret, this cycle time reference greatly simplified certain user inputs. Physical events occur at fixed time intervals from the engine valve actuation. Thus, the normalized time provides an ideal frame of reference for the user to specify certain regions of the cycle, such as the firing window or purge air flow, for processing. Figure 11 shows several engine events at their corresponding normalized times.

Signal Interruptions

When a detonation wave passed the detector, vibration, combined with the beam steering introduced by the density gradient of the propagating wave, caused the laser and detector to momentarily misalign. This drop in signal results in an abnormally high reading for the equivalence ratio. Figure 13 shows an output equivalence ratio plot including this phenomenon. While the misalignment did provide quantitative information about the wave speed and position of the detonation within the cycle, the value contaminated the equivalence ratio data. Fortunately, the spike does not occur in the fill region of the cycle. In addition, provided that the ignition delay is held constant, the spike appears at a roughly constant normalized time. Thus, the user is able to specify the region of the cycle in which the detonation spike will occur, and the search algorithm can ignore values in that range when calculating the maximum achieved equivalence ratio.

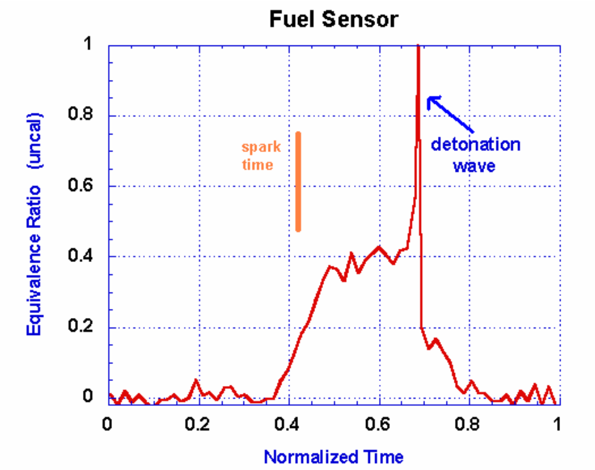

Figure 13. Output equivalence ratio signal with beam steering anomaly.

Conclusions

A suite of software tools has been developed to allow the efficient interpretation of multi-gigabyte sets of pulsed detonation engine data. Dynamic pressure transducers were analyzed to gain insights into detonation wave behavior. Various algorithms were designed to sift through several million points, locating each detonation, producing small representative point sets for easy graphing and numerical analysis, and directly calculating wave speeds, thrust, pressures, and work outputs. In addition, several filtration techniques were developed to reduce signal noise and utilize stable pressure traces as baselines for contaminated or low-amplitude signals. Pressure data was then synchronized to high speed video, providing qualitative insights into the temporal and spatial behaviors of the propagating detonation wave. This work also verified that the visual manifestations and pressure pulse of a detonation wave were virtually collocated.

Additional noise elimination techniques and batch processing algorithms were also required for equivalence ratio data. By including a cycle timing reference signal with the data, synchronizing the information stream with the physical engine behavior was greatly simplified. Savitzky-Golay filtering and floating average reference lines allowed fluctuating data with unpredictable noise and baseline characteristics to be correctly post-processed. Finally, by normalizing the cycle time, key cycle events could be easily located and manipulated with minimal user interaction.

As PDE experiments continue to become more intricate and greater numbers of diverse sensing systems are utilized simultaneously at ever-increasing acquisition rates, automated processing will become even more crucial to successful research endeavors. Eventually, numerous data types will be processed at near-real time to provide immediate feedback during testing. In the future, real-time systems utilizing these signals for closed loop feedback control of fuel injection, ignition, and throttling of pulsed detonation engines will require even more intelligent analysis algorithms.

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References

1. Schauer, F. R., Stutrud, J. S., and Bradley, R. P., "Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications," AIAA Paper 2001-1129 (2001).
2. Frankey, B. M., Schauer, F. R., Stutrud, J. S., and Bradley, R. P., "Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications," AIAA Paper 2002-0474 (2002).

3. Meyer, T. R., Hoke, J. L., Brown, M. S., Gord, J. R., and Schauer, F. R., "Experimental Study of Deflagration-to-Detonation Enhancement Techniques in a H_2/Air Pulsed-Detonation Engine," AIAA Paper No. 2002-3720, *AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit,* Indianapolis, IN, July 7-10, (2002).

4. Meicenheimer, H., Brown, M. S., Gord, J. R., "Molecular Emission as a Monitor of Combustion Chemistry," *Rocky Mountain Conference on Analytical Chemistry Luminescence Symposium*, Denver, Colorado, July, (2002).

5. Brown, M. S., "Emission and Absorption Based Sensors for the Pulsed Detonation Engine," *Turbine Engine Technology Symposium*, Dayton, Ohio, September 12, (2002).

6. Brown, M. S., Personal Communication, Innovative Scientific Solutions Incorporated, 20 December (2002).